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RADIO TELEMETRY FORMULA APPLICATIONS, A PRACTICAL USERS GUIDE

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
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The relationship between the various parameters of a frequency-modulated (FM) or double frequency-modulated (FM/FM) radio telemetry link and the resulting output signal-to-noise ratios are presented. Most of the relationships have been presented in varying degrees of applicability, but the purpose of this report is to present formulas that can be used as a quick reference for telemetry system designers. The mathematical derivation of all equations can be found in various radio telemetry and communications textbooks and papers.

20a. (continued)

The basic radio frequency link transmission formula with a sample calculation is also presented.

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I. INTRODUCTION

Frequently a need exists to calculate the required radio-frequency (RF) carrier deviation, receiver intermediate-frequency (IF) bandwidth, and the postdetection signal-to-noise (SNR) ratios in a given frequency modulation (FM) or double frequency-modulation (FM/FM) transmission link. Also, when certain postdetection SNR requirements are established, the link parameters must be correspondingly specified.

The elements of a typical FM or FM/FM transmission link are shown in Figure 1. An FM link would begin with the transmitter modulator input and terminate at the receiver-demodulator output after postdetection filtering. An FM/FM link would begin at the subcarrier oscillator input and terminate at the subcarrier discriminator low-pass filter output. The modulating data signals considered will be assumed sinusoidal and periodic; however,this is not a limitation, since the postdetection SNR derived can be considered to apply to aperiodic signals during their time of occurrance. The general and special case formulas for calculating the elements of Figure 1 are given in Section II of the this report. The special case formulas are for the Interrange Instrumentation Group (IRIG)[1] proportional bandwidth (PBW) and constant-bandwidth (CBW) channels. Sample calculations are made where appropriate. Section III presents the formulas required for calculating the parameters involved in the radio-frequency transmission link.

The symbols used in Section II are defined in the List of Symbols.

II. SIGNAL-TO-NOISE RATIO IMPROVEMENT FORMULAS FOR FREQUENCY-MODULATED AND DOUBLE FREQUENCY-MODULATED RADIO LINKS

A. General Formulas for Frequency-Modulated Radio Links

1. Single FM System - The formula used for calculating the output SNR versus the input SNR (same as the second detection system in an FM/FM link) is

$$SNR_{out} = SNR_{in} \left[\frac{\sqrt{1.5}\ (B_{if})^{1/2}\ \Delta F_c}{(F_m)^{3/2}} \right] . \tag{1}$$

2. First Detection Process in an FM/FM System - To calculate the subcarrier filter output SNR versus the carrier input SNR,

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1 *Telemetry Working Group, Interrange Instrumentation Group, "Telemetry Standards (Revised January 1971)," Secretariat, Range Commanders Council, Document 106-71.*

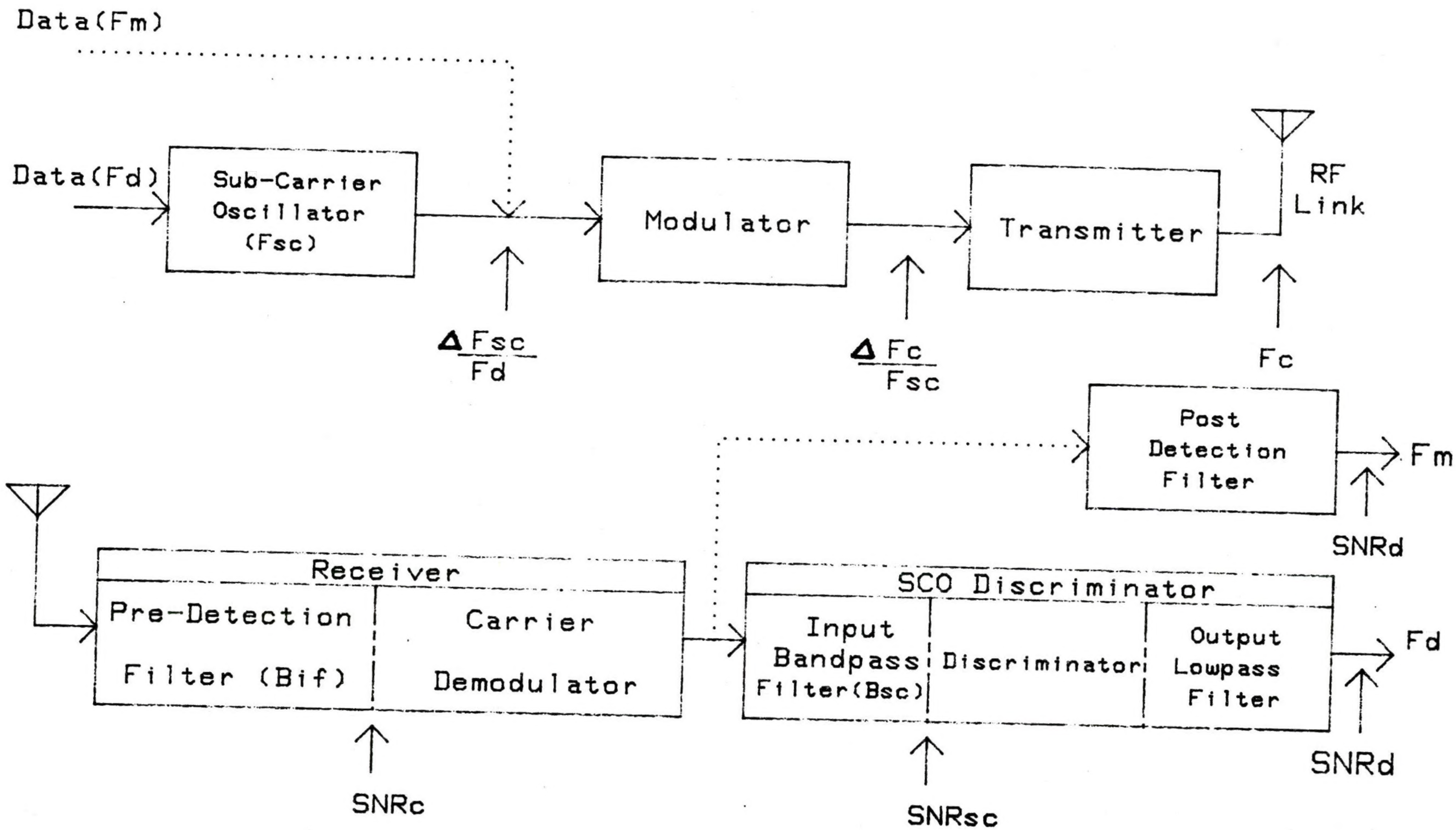

Figure 1. Elements of an FM or FM/FM Transmission Link

$$SNR_{sc} = SNR_c \left[\frac{\sqrt{1.5}\ (B_{if})^{1/2}\ \Delta F_c}{(F_u{}^3 - F_\ell{}^3)^{1/2}}\right] \quad (2)$$

is used.

For subcarrier peak deviations, small in comparison to the subcarrier center frequency, (i.e., the IRIG channels) Eq. (2) can be simplified to

$$SNR_{sc} = SNR_c \left[\frac{(B_{if})^{1/2}\ \Delta F_c}{(2B_{sc})^{1/2}\ F_{sc}}\right] . \quad (3)$$

3. Second Detection Process in an FM/FM System - The equation used for calculating the data output SNR versus the subcarrier filter output SNR is given by

$$SNR_d = SNR_{sc} \left[\frac{(1.5)^{1/2}\ (B_{sc})^{1/2}\ \Delta F_{sc}}{(F_d)^{3/2}}\right] . \quad (4)$$

4. Overall FM/FM System - The data output SNR versus the carrier input SNR is calculated from

$$SNR_d = SNR_c \left[\frac{(0.75)^{1/2}\ (B_{if})^{1/2}\ \Delta F_c\ \Delta F_{sc}}{(F_d)^{1/2}\ F_{sc}\ F_d}\right] . \quad (5)$$

B. First (Carrier) Detection Process for the Standard Interrange Instrumentation Group Channels

These equations are used for calculating the subcarrier filter output SNR versus the carrier input SNR using a constant K derived from the IRIG standard subcarrier bandwidths and deviations. This is represented by a special case of Eq. (3).

1. Proportional Bandwidth Channels

Using the term $(2 B_{sc})^{1/2}$ from Eq. (3), where

$$(2 B_{sc})^{1/2} = (2x2x \frac{\% \text{ deviation}}{100} \text{ x } F_{sc})^{1/2} ,$$

and introducing

$$K = (\frac{100}{4 \text{ x } \% \text{ deviation}})^{1/2} ,$$

Eq. (3) then becomes

$$SNR_{sc} = SNR_c \left[\frac{K (B_{if})^{1/2} \Delta F_c}{(F_{sc})^{3/2}}\right] . \qquad (6)$$

The constant K is 1.826 for IRIG Channels 1-25 (± 7 1/2 % deviation) and 1.291 for IRIG Channels A-L (± 15% deviation).

2. Constant Bandwidth Channels

Again examining the term $(2 B_{sc})^{1/2}$ from Eq. (3) for this case,

$$(2 B_{sc})^{1/2} = (2x2x \Delta F_{sc})^{1/2} = 1/K .$$

Eq. (3) then becomes

$$SNR_{sc} = SNR_c \left[\frac{K (B_{if})^{1/2} \Delta F_c}{F_{sc}}\right] . \qquad (7)$$

The magnitude of K is

11.18×10^{-3} for ± 2 kHz deviation,
7.9×10^{-3} for ± 4 kHz deviation,
5.59×10^{-3} for ± 8 kHz deviation,
3.95×10^{-3} for ± 16 kHz deviation, or
2.79×10^{-3} for ± 32 kHz deviation.

C. Second (Subcarrier) Detection Process for the Standard Interrange Instrumentation Group Channels

These equations are used for calculating the data output SNR versus the subcarrier filter output SNR using a constant K derived from the IRIG standard subcarrier bandwidths and deviations. These are represented by a special case of Eq. (4).

1. Proportional Bandwidth Channels

Using the terms $(1.5)^{1/2}\ (B_{sc})^{1/2}\ \Delta F_{sc}$ from Eq. (4),

$$(1.5)^{1/2}\ (B_{sc})^{1/2}\ \Delta F_{sc} = (1.5)^{1/2}\ \left(1.05 \times 2 \times \frac{\%\ \text{deviation}}{100}\ F_{sc}\right)^{1/2} \left(\frac{\%\ \text{deviation}}{100}\ F_{sc}\right),$$

and

$$K = (3.15)^{1/2}\ \left(\frac{\%\ \text{deviation}}{100}\right)^{3/2} .$$

Eq. (4) then becomes

$$SNR_d = SNR_{sc} \left[\frac{K\ (F_{sc})^{3/2}}{(F_d)^{3/2}}\right], \qquad (8)$$

where the values for K are 3.65×10^{-2} for IRIG Channels 1-25 (± 7 ½ % deviation) and 10.31×10^{-2} for IRIG Channels A-L (± 15% deviation).

2. Constant Bandwidth Channels

Using the terms $(1.5)^{1/2} \; (B_{sc})^{1/2} \; \Delta F_{sc}$ from Eq. (4) ,

$$(1.5)^{1/2} \; (B_{sc})^{1/2} \; \Delta F_{sc} = (1.5)^{1/2} (1.05 \text{x} 2 \text{x} \; \Delta F_{sc})^{1/2} \; \Delta F_{sc} = K ,$$

where

$$K = (3.15)^{1/2} \; (\Delta F_{sc})^{3/2} ,$$

Eq. (4) then becomes

$$SNR_d = SNR_{sc} \left[\frac{K}{(F_d)^{3/2}}\right] , \qquad (9)$$

where K is 1.59×10^5 for ± 2 kHz deviation,
4.49×10^5 for ± 4 kHz deviation,
12.70×10^5 for ± 8 khz deviation,
35.92×10^5 for ± 16 kHz deviation, or
101.60×10^5 for ± 32 kHz deviation.

D. Composite (Overall) Signal-to-Noise Ratio for the Standard Interrange Instrumentation Group Channels

These equations are used for calculating the data output SNR versus the carrier input SNR using a constant K derived from the IRIG standard subcarrier bandwidths and deviations. (Special case of Eq. (5)).

1. Proportional Bandwidth Channels

Using the terms $\dfrac{(0.75)^{1/2} \; \Delta F_{sc}}{F_{sc}}$ from Eq. (5) ,

it can be shown that

$$\frac{(0.75)^{1/2}\ \Delta F_{sc}}{F_{sc}} = \frac{(0.75)^{1/2}\ (\%\ \text{Deviation x}\ F_{sc})}{100\ F_{sc}} = K\ .$$

Simplifying all terms,

$$K = 0.866\text{x}10^{-2}\ (\%\ \text{deviation}),$$

and Eq. (5) then becomes

$$SNR_d = SNR_c\ [\frac{K\ (B_{if})^{1/2}\ \Delta F_c}{(F_d)^{3/2}}]\ , \qquad (10)$$

where K is $6.495\text{x}10^{-2}$ for IRIG Channels 1-25 (± 7 1/2 % deviation) or $12.99\text{x}10^{-2}$ for IRIG Channels A-L (± 15% deviation).

The formula for calculating the RF carrier deviation (ΔF_c) when SNR_d is specified as 40 db (100:1) at a receiver threshold of SNR_c = 10 db (3.162:1) is

$$\Delta F_c = \frac{31.63\ (F_d)^{3/2}}{K\ (B_{if})^{1/2}}\ . \qquad (11)$$

From the relationships

$$DR = \frac{\Delta F_{sc}}{F_d}\ ,$$

and

$$\Delta F_{sc} = PF_{sc}\ ,$$

where P, a constant, is either 0.075 or 0.15,

Eq. (11) becomes

$$\Delta F_c = \frac{31.63\ (P)^{3/2}}{K(B_{if})^{1/2}\ \ (DR)^{3/2}} \times (F_{sc})^{3/2} \quad . \tag{12}$$

In a proportional bandwidth system, P, K, B_{if}, and DR are constant and it can be seen that the RF carrier deviation (ΔF_c) varies with respect to $(F_{sc})^{3/2}$. This fact illustrates the classical "3/2" power pre-emphasis characteristic.

2. Constant Bandwidth Channels

Using the terms $(0.75)^{1/2}\ \Delta F_{sc}$ for the value of K, Eq. (5) becomes

$$SNR_d = SNR_c \left[\frac{K\ (B_{if})^{1/2}\ \Delta F_c}{F_{sc}(F_d)^{3/2}}\right] \quad , \tag{13}$$

where K is 1.732×10^3 for ± 2 kHz deviation,
3.464×10^3 for ± 4 kHz deviation,
6.928×10^3 for ± 8 kHz deviation,
13.856×10^3 for ± 16 kHz deviation, or
27.712×10^3 for ± 32 kHz deviation.

The formula for calculating the RF carrier deviation (ΔF_c) when SNR_d is specified as 40 db (100:1) at a receiver threshold of SNR_c = 10 db (3.162:1) is

$$\Delta F_c = \frac{31.63\ F_{sc}\ (F_d)^{3/2}}{K\ (B_{if})^{1/2}} \quad . \tag{14}$$

From the relationship

$$DR = \frac{\Delta F_{sc}}{F_d} \quad ,$$

Eq. (14) then becomes

$$\Delta F_c = \frac{31.63\ (\Delta F_{sc})^{3/2}}{K(B_{if})^{1/2}\ \ (DR)^{3/2}} \times F_{sc} \quad . \tag{15}$$

In a constant bandwidth system, ΔF_{sc}, K, B_{if} and DR are constant, and it can be seen that the RF carrier deviation (ΔF_c) varies proportionately with respect to F_{sc}.

3. Sample Calculation of RF Carrier Deviation

The requirement for this example is to find the required RF carrier deviations for five standard proportional bandwidth channels in order to have a data output SNR of 40 db at receiver threshold. An FM/FM link requires an SNR_c = 10 db. The parameters given include a receiver IF bandwidth of 500 kHz, the IRIG channels selected are 14 thru 18, and the deviation ratio (DR) is 5.

From Eq. (12),

$$\Delta F_c = \frac{31.63\ (.075)^{3/2}\quad (F_{sc})^{3/2}}{6.495\times10^{-2}(500\times10^3)^{1/2}\ (5)^{3/2}}\quad , \text{ and}$$

$$\Delta F_c = 1.265\times10^{-3}(F_{sc})^{3/2}\quad .$$

TABLE 1. SAMPLE CALCULATION

Channel No.	F_{sc} (kHz)	ΔF_c (kHz)	M
14	22	4.13	0.19
15	30	6.57	0.22
16	40	10.12	0.25
17	52.5	15.22	0.29
18	70	23.43	0.33

E. Receiver Intermediate-Frequency Bandwidth Considerations

There seems to be a number of schools of thought for calculating the required receiver IF bandwidth for an FM/FM multiplex system. Scwartz,[2]

[2] *M. Scwartz, Information Transmission, Modulation and Noise, McGraw Hill, New York, 1959.*

Gruenberg,[3] and Stein[4] state that a general rule of thumb equation based on a single-frequency sinusoidal modulating signal is,

$$B_{if} = 2\ (\Delta F_c + F_{sc}) \quad , \tag{16}$$

where F_{sc} is taken as the highest subcarrier frequency in the multiplex system. This equation designates a bandwidth that is wide enough to include all sideband current pairs that are greater than 10% of the amplitude of the unmodulated carrier. If the unmodulated carrier and sideband current amplitudes were converted to power levels,then Eq. (16) would include all sidebands having power levels greater than 1% of the unmodulated carrier power.

The Radio Engineers Handbook[5] states that an estimate of the IF bandwidth required for transmission of a complex modulation signal is given by

$$B_{if} = 2(\Delta F_c + 2\ F_{sc}) \quad . \tag{17}$$

This equation, based on a single-frequency sinusoidal modulating signal, designates a bandwidth that includes all sideband current pairs greater than 4% of the amplitude of the unmodulated carrier. This corresponds to 0.16% for power levels.

Eqs. (16) and (17) plus a table of Bessel functions can be plotted in convenient form as shown in Figures 2 and 3. The Bessel functions are plotted to include sideband current pairs that are greater than 1% of the unmodulated carrier. The IF bandwidth on the plots has been normalized to the subcarrier frequency for convenience.

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3 *E.L. Gruenberg, Handbook of Telemetry and Remote Control, McGraw Hill, New York, 1967.*

4 *S. Stein and J.J. Jones, Modern Communication Principles, McGraw Hill, New York, 1967.*

5 *ITT, Reference Data for Radio Engineers, 5th Edition, Howard W. Sams, New York, 1970.*

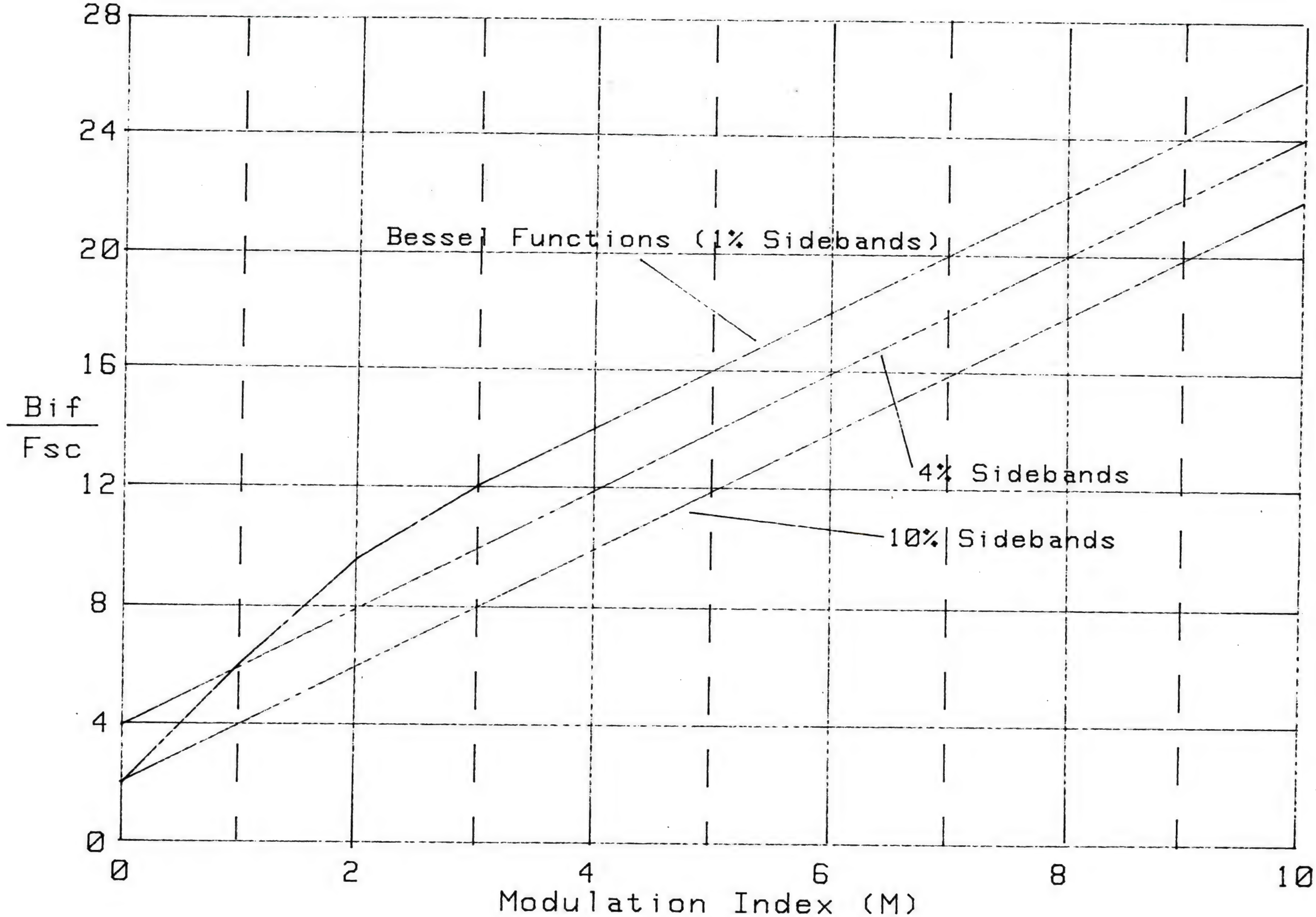

Figure 2. Receiver Bandwidth vs Modulation Index, Large M

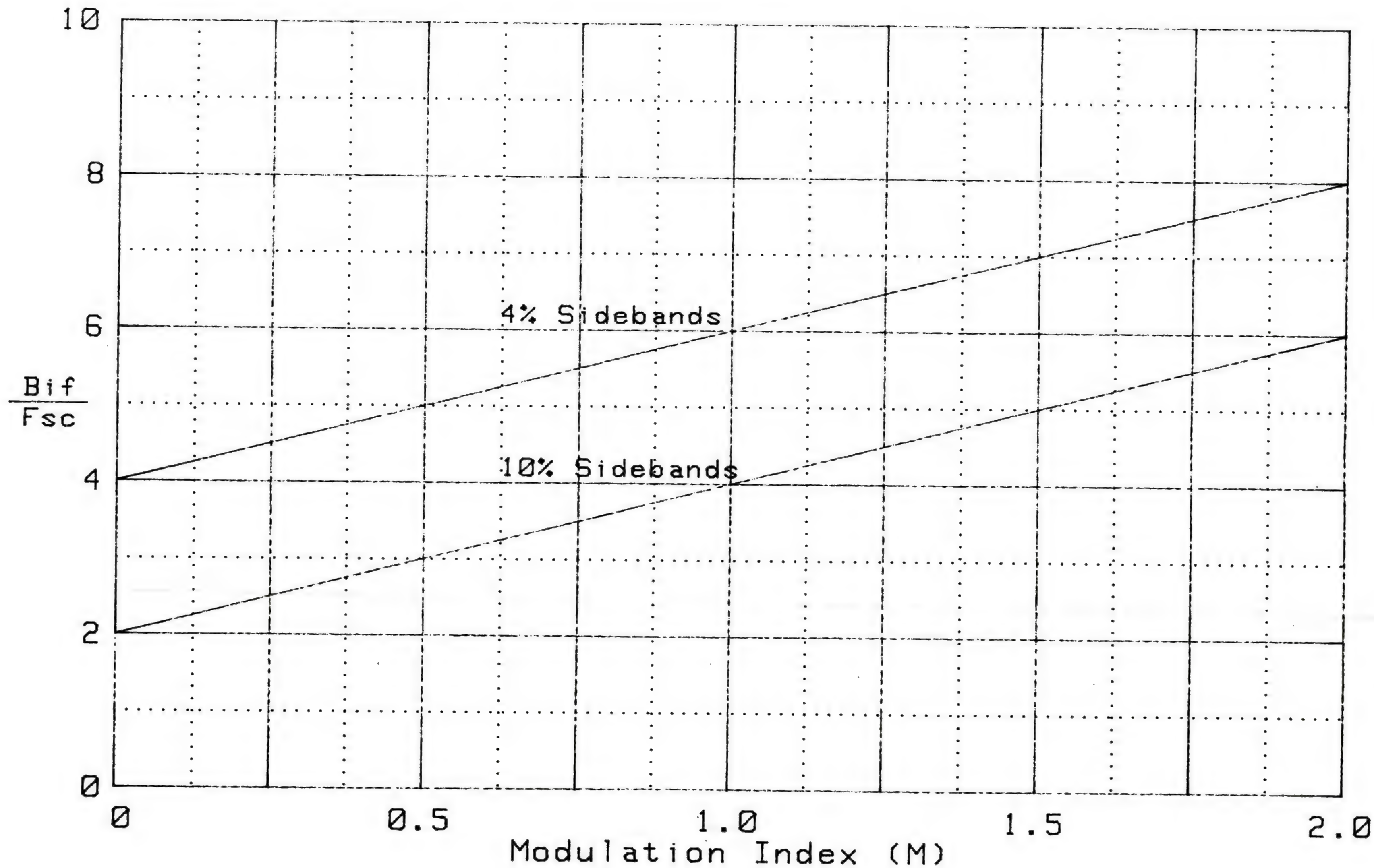

Figure 3. Receiver Bandwidth vs Modulation Index, Small M

F. Derivation of Optimum Intermediate-Frequency Bandwith and Radio-Frequency Deviation for a Single Subcarrier Frequency

The optimum IF bandwidth and RF carrier deviation for a single subcarrier frequency, (usually the highest SCO frequency in a multiplex) is derived from Eq. (5),

$$SNR_d = SNR_c \left[\frac{\sqrt{0.75}\,(B_{if})^{1/2}}{(F_d)^{1/2}}\;\frac{\Delta F_c}{F_{sc}}\;\frac{\Delta F_{sc}}{F_d}\right] .$$

Assuming that

$$C = \frac{SNR_D}{SNR_c\sqrt{0.75}} , \qquad (18)$$

$$\Delta F_{sc} = R\, F_{sc} \quad \text{, and} \qquad (19)$$

$$F_d = K\, F_{sc} , \qquad (20)$$

and substituting Eqs. (17), (18), (19), and (20) in Eq. (5),

$$C = \frac{(2\,\Delta F_c + 4\,F_{sc})^{1/2}}{(K\,F_{sc})^{1/2}}\;\frac{\Delta F_c}{F_{sc}}\;\frac{R\,F_{sc}}{K\,F_{sc}} .$$

Simplifying and squaring all terms,

$$C^2 = \frac{(2\ \Delta F_c + 4\ F_{sc})\ \Delta F_c^{\ 2}\ R^2)}{(K\ F_{sc})\ \ F_{sc}^{\ 2}\ K^2} \quad .$$

Multiplying all terms and separating,

$$C^2 = \frac{2\ \Delta F_c^{\ 3}\ R^2}{K^3\ F_{sc}^{\ 3}} + \frac{4\ F_{sc}\ \Delta F_c^{\ 2}\ R^2}{K^3\ F_{sc}^{\ 3}} \quad .$$

Simplifying and substituting M for $\Delta F_c/F_{sc}$,

$$C^2 = \frac{2M^3R^2}{K^3} + \frac{4M^2R^2}{K^3} \quad ,$$

and we arrive at the result

$$M^3 + 2\ M^2 = \frac{C^2\ K^3}{2\ R^2} \quad . \tag{21}$$

A sample problem, given that SNR_d = 100 (40 db), ΔF_{sc} = 32 kHz, SNR_c = 3.162 (10 db), F_d = 8 kHz, and F_{sc} = 256 kHz results in the following:

$$C = \frac{100}{3.162 \times 0.866} = 36.518 \text{ (from Eq. (18))},$$

$$R = \frac{32 \times 10^3}{256 \times 10^3} = 0.125 \text{ (from Eq. (19)), and}$$

$$K = \frac{8 \times 10^3}{256 \times 10^3} = 3.125 \times 10^{-2} \text{ (from Eq. (20))}.$$

Solving Eq. (21),

$$M^3 + 2M^2 = 1.302 \quad .$$

Using the solution for solving a cubic equation,

$$M = 0.695 \quad \text{(A positive real root).}$$

Since $M = \Delta F_c / F_{sc}$ then

$$\Delta F_c = 177.92 \text{ kHz},$$

and from Eq. (17),

$$B_{if} = 1379.84 \text{ kHz}.$$

The value of M will vary for each of the IRIG constant bandwidth channels but will remain constant for each set of the proportional bandwidth channels. The values of M for the PBW channels are $M = 0.4076$ for $\pm\ 7\frac{1}{2}\%$ deviation channels and $M = 0.559$ for $\pm\ 15\%$ deviation channels.

III. RADIO-FREQUENCY LINK TRANSMISSION FORMULA

The radio-frequency link transmission formula is a very useful tool for calculating a safety factor when all link parameters are defined, or determining any of the individual factors in the link. The basic formula can be stated in terms of power levels relative to a fixed reference. For this discussion a reference of 1 milliwatt into 50 ohms (0 dbm) will be used. This formula is a convenient tool for link calculations since all parameters are expressed in the same terms instead of meters, seconds, Hertz, etc.

A. Basic Transmission Formula

The basic equation for transmission is

$$P_t = R_n + SNR - G_t - G_r + L + PL + SF \quad , \tag{22}$$

where P_t is the transmitter power (dbm), R_n is the equivalent noise input of receiving system (dbm) (this term will be discussed in Part B), SNR is the signal-to-noise ratio required for a particular type of transmission (normally 9-12 db is required for an FM/FM Telemetry link), G_t is the transmitter antenna gain (db), G_r is the receiving antenna gain (db), L represents the Miscellaneous losses (polarization fade, cable losses, vswr, etc., 10 db is normally used), and PL is the Path loss or attenuation (db). The latter term is represented by

$$PL = C + 20 \text{ Log } f + 20 \text{ Log } d^{(5)}, \tag{23}$$

where f is the transmitter frequency (MHz), d is the distance, and C = 36.58 when d is expressed in miles (statute), -37.87 when d is given feet, and -27.55 when d is cited in meters. The term SF in Eq. (22) is the Safety factor (db).

B. Equivalent Noise Input of Receiving System (Rn)

The formula for the term R_n of Eq. (22) is,

$$R_n = K \; T_e \; B_{if} \quad (\text{Watts})^{(5)} \tag{24}$$

where K is equal to 1.38×10^{-23} joules/^{0}K (Boltzmanns constant), T_e is the effective receiving system noise temperature (^{0}K), and B_{if} is the Receiver IF bandwidth (Hz). Eq. (24) can be expressed in Logarithmic notation referenced to 0 dbm,

$$R_n = - 198.6 + 10 \text{ Log } T_e + 10 \text{ Log } B_{if}. \tag{25}$$

The term T_e in Eq. (24) and Eq. (25) can be calculated from

$$T_e = T_R + TA/L + T_L \, (1 - 1/L), \tag{26}$$

where T_R is the receiving system noise temperature referred to its input (^{0}K), T_A is the effective antenna temperature (^{0}K), T_L is the temperature of losses between antenna and receiving system (normally 290^{0}K), and L is the power-loss ratio between antenna and receiving system. In most cases the term T_A/L can be neglected for frequencies above 20 MHz.

Some receiving systems are composed of a preamplifier located near the antenna and a receiver located at a distance in a building or van. For this case the formula for the system noise temperature of networks in cascade is

$$T_R = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \ldots , \qquad (27)$$

where T_1 is the noise temperature of first network (^{0}K), T_2 is the noise temperature of second network (^{0}K), G_1 is the effective gain (power ratio) between first and second networks (i.e. gain minus losses), and G_2 is the effective gain (power ratio) between second and third networks.

Most specifications for preamplifiers and receivers state the system noise temperature in terms of a db noise figure. This noise figure can be converted to noise temperature by use of the following equation,

$$T = (Nf - 1), \qquad (28)$$

where Nf is the noise factor (power ratio of the noise figure) and T_o = 290^{0}K.

A useful formula for finding the overall noise figure of a preamplifier and receiver in cascade can be found by substituting Eq. (28) in Eq. (27) which yields

$$(Nf_R - 1)\, T_o = (Nf_1 - 1)\, T_o + \frac{(Nf_2 - 1) T_o}{G_1} \; .$$

Simplifying all terms,

$$Nf_R = Nf_1 + \frac{(Nf_2 - 1)}{G_1} \; . \qquad (29)$$

The cascaded noise figure is then

$$NF_R = 10 \text{ Log } Nf_R. \tag{30}$$

C. **Sample Calculation for the Safety Factor in a Radio-Frequency Transmission Link**

Presuming that the following parameters are given for a transmission link,

transmitter power (P_t) = 250 milliwatts (+ 24 dbm),
transmitter antenna gain (G_t) = + 4 db,
receiver antenna gain (G_r) = + 16 db,
distance (d) = 12 miles,
frequency (f) = 1500 MHz,
receiver IF bandwidth (B_{if}) = 500 kHz,
preamplifier gain = 18 db (63:1) with a noise temperature = 600 ^{0}K (NF = 4.87 db),
receiver noise temperature = 3000 ^{0}K (NF = 10.55 db), and
cable losses, for antenna to preamplifier = 5 db (3.16:1) and for preamplifier to receiver = 6 db (3.98:1),

all parameters of Eq. (22) are defined except R_n and PL. They may be calculated as follows:

$$TR = 600 + \frac{3000}{(63-3.98)} \quad \text{(from Eq. (27)), yielding}$$

$$TR = 651^0K, \text{ and}$$

$$T_e = 651 + 290 \left(1 - \frac{1}{3.16}\right) \quad \text{(from Eq. (26)), or}$$

$$T_e = 849^0K.$$

From Eq. (25)

$$R_n = -198.6 + 10 \text{ Log } 849 + 10 \text{ Log } (500\text{x}10^3), \text{ which gives}$$

$$R_n = -112 \text{ dbm (rounded off).}$$

From Eq. (23)

$$PL = 36.58 + 20 \text{ Log } 1500 + 20 \text{ Log } 12, \text{ or}$$

$$PL = 122 \text{ db (rounded off).}$$

The safety factor (SF) is calculated by inserting all given and computed values into Eq. (22),

$$P_t = R_n + SNR - G_t - G_r + L + PL + SF, \text{ which gives} \quad (22)$$

$$24 = -112 + 12 - 4 - 16 + 10 + 122 + SF, \text{ and the result}$$

$$SF = 12 \text{ db.}$$

The significance of the safety factor is that the signal at the input of the receiver will be 12 db greater than that required for the FM threshold of the receiver at a maximum range of 12 miles.

The radio link parameters can be expressed in tabular form, but the use of a level diagram permits easy visualization and helps to prevent errors of sign or omission during link calculations. Figure 4 presents a convenient form using the parameters from the sample calculation.

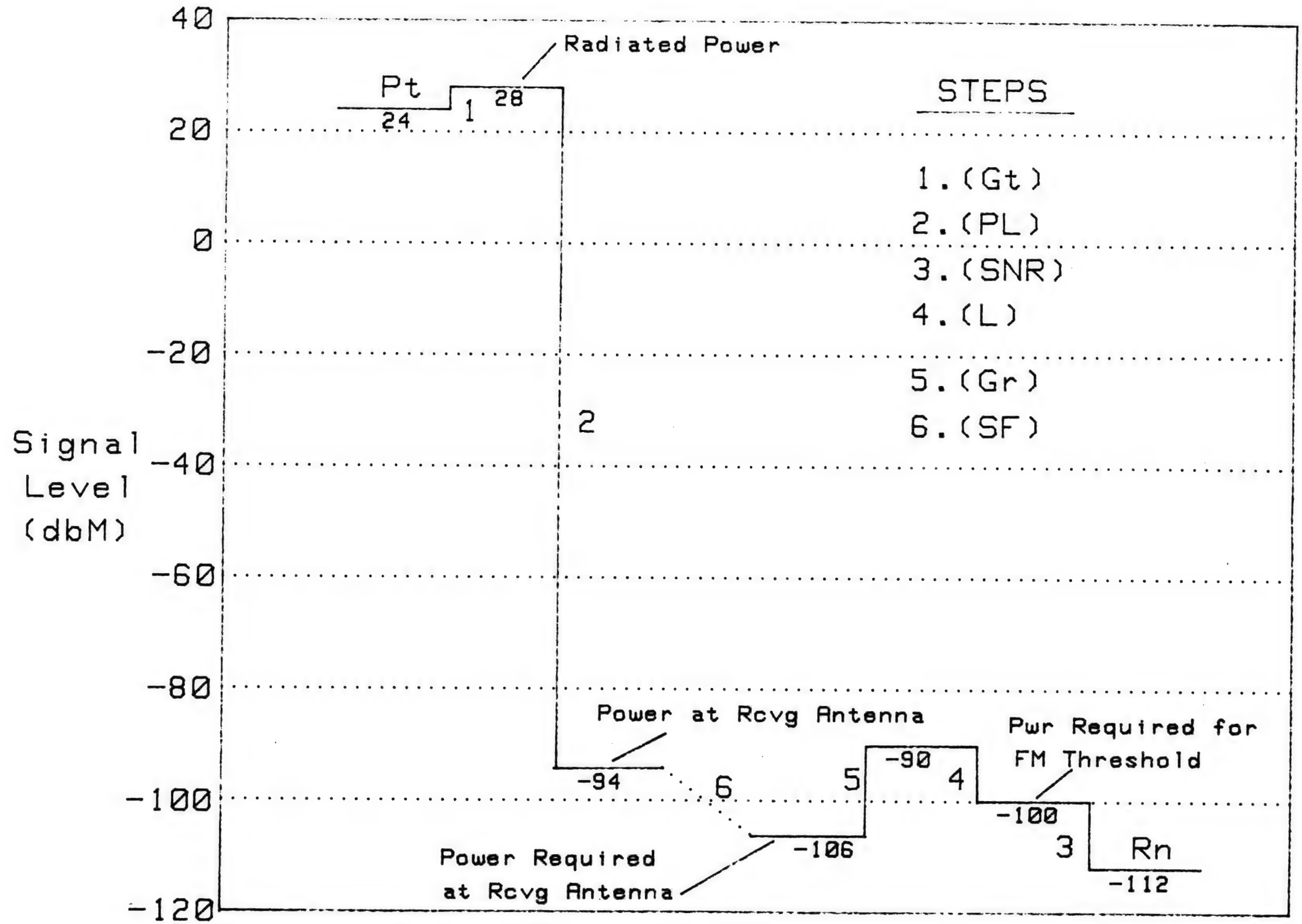

Figure 4. Radio Transmission Link Level Diagram

IV. SUMMARY

The relationships and formulas presented in this report should give the FM/FM telemetry system designer enough information to design a practical operating telemetry system. Further information on the derivation of the formulas and additional theory can be found in the list of references.

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1. Telemetry Working Group, Interrange Instrumentation Group, "Telemetry Standards (Revised January 1971)," Secretariat, Range Commanders Council, Document 106-71.

2. M. Scwartz, Information Transmission, Modulation and Noise, McGraw Hill, New York, 1959.

3. E.L. Gruenberg, Handbook of Telemetry and Remote Control, McGraw Hill,New York, 1967.

4. S. Stein and J.J. Jones, Modern Communication Principles, McGraw Hill, New York, 1967.

5. ITT, Reference Data for Radio Engineers, 5th edition, Howard W. Sams, New York, 1970.

APPENDIX A

COMPUTER PROGRAM FOR THE CALCULATION OF TELEMETRY RF DEVIATIONS AND RECEIVER IF BANDWIDTH (WRITTEN IN BASIC LANGUAGE FOR THE HEWLETT PACKARD MODEL 9845 COMPUTER)

```
CALCULATION OF TELEMETRY R.F. DEVIATIONS AND I.F. BANDWIDTH (3/28/75)
---  OPTIONS: 1=DEV FOR ACTUAL BW, 2=OPTIMUM DEV VS BW, 3=BOTH ---
*****************************************************************
```

```
10    OPTION BASE 1!        TMDEV
20    PRINTER IS 0
30    PRINT "CALCULATION OF TELEMETRY R.F. DEVIATIONS AND I.F. BANDWIDTH (3/28/7
5)"
40    PRINT "---  OPTIONS: 1=DEV FOR ACTUAL BW, 2=OPTIMUM DEV VS BW, 3=BOTH ---"
50    PRINT "*****************************************************************
***"
60    PRINT LIN(3)
70    INPUT "WHAT IS INPUT OPTION =",O
80    IF O=1 THEN 110
90    IF O=2 THEN 130
100   IF O=3 THEN 150
110   PRINT "*** CALC OF DEVIATION FOR ACTUAL BANDWIDTH ***"
120   GOTO 160
130   PRINT "*** CALCULATION OF OPTIMUM DEVIATION VS BANDWIDTH ***"
140   GOTO 160
150   PRINT "*** CALCULATION OF OPTIMUM DEV VS BW AND DEV FOR ACTUAL BW ***"
160   PRINT LIN(2)
170   INPUT "WHAT IS INPUT CARRIER SNR = (DB)",N1
180   INPUT "WHAT IS OUTPUT DATA SNR = (DB)",N3
190   PRINT "INPUT CARRIER SNR = ";N1;" DB";"  OUTPUT DATA SNR = ";N3;" DB"
200   PRINT
210   N2=10^(N1/20)
220   N4=10^(N3/20)
230   C9=N4/(N2*SQR(.75))
240   INPUT "WHAT IS SCO CENTER FREQ (KHz)",F
250   INPUT "WHAT IS SCO FREQ DEV (KHz)",F1
260   INPUT "WHAT IS SCO DEVIATION RATIO",D
270   PRINT "SCO CENTER FREQ = ";F;" KHz   SCO FREQ DEV = ";F1;" KHz   DEV RATIO
 = ";D
280   PRINT
290   F=F*1000
300   F1=F1*1000
301   F3=F1/D
310   IF O=1 THEN 1170
320   PRINT "C9 = ";C9
330   PRINT
340   P=1
350   Q=0
360   R=-(C9^2/(2*D^3))*F1/F
370   A=1/3*(3*Q-P^2)
380   B=1/27*(2*P^3-9*P*Q+27*R)
390   C=B^2/4+A^3/27
400   PRINTER IS 0
410   PRINT "P= ";P;" Q= ";Q;" R= ";R
420   PRINT "A= ";A;" B= ";B;" C= ";C
430   PRINT
440   IF C<0 THEN Unequal
450   IF C>0 THEN Imag
460   PRINT "THERE ARE THREE REAL ROOTS, TWO ARE EQUAL"
470   PRINT
480   S1=1
490   B1=-B/2
500   IF B1>=0 THEN 520
510   S1=-1
520   M1=S1*ABS(B1)^(1/3)*2-P/3
530   M2=-S1*ABS(B1)^(1/3)-P/3
```

```
540    M3=M2
550    M=M1
560 Rep:PRINT "M1= ";M1;" M2= ";M2;" M3= ";M3
570    PRINT
580    PRINT "M= ";M
590    PRINT
600    S1=M1^3+2*M1^2+R
610    S2=M2^3+2*M2^2+R
620    S3=M3^3+2*M3^2+R
630    PRINT "S1= ";S1;" S2= ";S2;" S3= ";S3
640    GOTO Quit
650 Imag:A1=-(B/2)+SQR(C)
660    PRINT "THERE IS ONE REAL & TWO CONJUGATE IMAGINARY ROOTS"
670    PRINT
680    B1=-(B/2)-SQR(C)
690    S1=1
700    S2=1
710    IF A1>=0 THEN 730
720    S1=-1
730    IF B1>=0 THEN 750
740    S2=-1
750    A1=S1*ABS(A1)^(1/3)
760    B1=S2*ABS(B1)^(1/3)
770    PRINT "A1= ";A1;" B1= ";B1
780    PRINT
790    M1=A1+B1-P/3
800    M=M1
810    M2=-(A1+B1)/2-P/3
820    I2=(A1-B1)/2*SQR(3)
830    M3=M2
840    I3=-I2
850    PRINT "M1= ";M1
860    PRINT "M2= ";M2;" I2= ";I2
870    PRINT "M3= ";M3;" I3= ";I3
880    PRINT
890    PRINT "M= ";M
900    PRINT
910    S1=M1^3+2*M1^2-C9^2/(2*D^3)*F1/F
920    PRINT "S1= ";S1
930    GOTO Quit
940 Unequal:  T2=-(B/2)/SQR(-A^3/27)
950    PRINT "THERE ARE THREE REAL UNEQUAL ROOTS"
960    PRINT
970    T3=SQR(1-T2^2)
980    T=ATN(T3/T2)
990    IF T2>0 THEN 1010
1000   T=-T+PI
1010   T1=2*SQR(-A/3)
1020   M1=T1*COS(T/3)-P/3
1030   M2=T1*COS(T/3+2*PI/3)-P/3
1040   M3=T1*COS(T/3+4*PI/3)-P/3
1050   M=M1
1060   IF M2<M THEN 1080
1070   M=M2
1080   IF M3<M THEN 1100
1090   M=M3
1100   GOTO Rep
1110 Quit: F2=M*F/1000
1120   W=2*(F2*1000+2*F)/1000
1130   PRINT
1131 Imag1:IMAGE "OPT CARRIER DEV= ",DDD," KHz     OPT I.F. BW= ",DDDD," KHz"
1140   PRINT USING Imag1;F2;W
1150   IF O=2 THEN Blank
1160   PRINT
1170   INPUT "WHAT IS ACTUAL I.F. BW (Hz)",W1
1180   PRINT
```

```
1190  F2=C9*F*F3^1.5/(SQR(W1)*F1)
1191 Imag2:IMAGE "ACTUAL I.F. BW = ",DDDD," KHz   R.F. DEV = ",DDD," KHz"
1200  PRINT USING Imag2;W1/1000;F2/1000
1210  PRINT
1220  W2=2*(F2+F)
1221 Imag3:IMAGE "REQUIRED BW FOR R.F. DEV= ",DDDD," KHz"
1230  PRINT USING Imag3;W2/1000
1240 Blank:PRINT LIN(3)
1250  PRINTER IS 16
1260  STOP
1270  END
```

APPENDIX B

COMPUTER PROGRAM FOR THE CALCULATION OF THE SAFETY FACTOR FOR AN RF TRANSMISSION LINK (WRITTEN IN BASIC LANGUAGE FOR THE HEWLETT PACKARD MODEL 9845 COMPUTER)

CALCULATION OF SAFETY FACTOR FOR RF TRANSMISSION LINK
****

```
10    OPTION BASE 1  !     RFLINK
20    PRINTER IS 0
30    PRINT "          CALCULATION OF SAFETY FACTOR FOR RF TRANSMISSION LINK"
40    PRINT "          *************************************************"
50    PRINT LIN(2)
60    INPUT "ENTER TRANSMITTER POWER=(MW)",P1
70    PRINTER IS 16
80    INPUT "ENTER TRANSMITTER ANTENNA GAIN=(DB)",G1
110   PRINT PAGE
120   PRINTER IS 0
130   INPUT "ENTER RECEIVER ANTENNA GAIN MINUS CABLE LOSS TO PRE-AMP OR RCVR=(DB
)",G2
140   INPUT "ENTER TRANSMISSION RANGE=(FEET)",D
150   INPUT "ENTER TRANSMISSION FREQUENCY=(MHZ)",F
160   INPUT "ENTER RECEIVER I.F. BANDWIDTH=(HZ)",B
170   INPUT "ENTER PREAMPLIFIER GAIN=(DB), ENTER 0 WITHOUT PREAMPLIFIER",G3
180   INPUT "ENTER PREAMPLIFIER NOISE FIGURE=(DB), ENTER 0 WITHOUT PREAMPLIFIER"
,N1
190   INPUT "ENTER RECEIVER NOISE FIGURE=(DB)",N2
200   INPUT "ENTER CABLE LOSS(PREAMP-RCVR)=(DB)ENTER 0 IF NO PRE-AMP USED",L2
210   INPUT "ENTER REQUIRED  SIGNAL TO NOISE RATIO=(DB)",S
220   INPUT "ENTER SYSTEM MISCL LOSSES=(DB)",L
230   P=10*LGT(P1)
240   A=-37.87+20*LGT(F)+20*LGT(D)
250   N4=10^(N2/10)          !     RCVR NF
260   IF (G3=0) AND (N1=0) THEN 330
270   N3=10^(N1/10)       !     P.A. NF
280   G4=10^(G3/10)       !     P.A. GAIN
290   L4=10^(L2/10)       !     P.A. RCVR
300   N=N3+(N4-1)/(G4-L4)
310   T=(N-1)*290
320   GOTO 340
330   T=(N4-1)*290
340   R=-198.6+10*LGT(T)+10*LGT(B)
350   S1=P-R+G1+G2-S-L-A
360   PRINT "INPUT PARAMETERS"
370   PRINT
380   PRINT "     TRANSMITTING  POWER OUTPUT= ";P1;" MILLIWATTS"
390   PRINT "     SYSTEM        ANTENNA GAIN= ";G1;" DB"
400   PRINT
410   PRINT "     RECEIVING     ANTENNA GAIN= ";G2;" DB"
420   PRINT "     SYSTEM        PREAMPLIFIER NOISE FIGURE= ";N1;" DB,(0=NO PRE-
AMP)"
430   PRINT "                   PREAMPLIFIER GAIN= ";G3;" DB,(0=NO PRE-AMP)"
440   PRINT "                   RECEIVER NOISE FIGURE= ";N2;" DB"
450   PRINT "                   I.F. BANDWIDTH= ";B/1000;" KHz"
460   PRINT "                   REQUIRED SIGNAL TO NOISE RATIO= ";S;" DB"
470   PRINT
480   PRINT "     SYSTEM LOSSES PREAMPLIFIER TO RECEIVER= ";L2;" DB"
490   PRINT "                   MISCELLANEOUS= ";L;" DB"
500   PRINT
510   PRINT "     TRANSMISSION  RANGE= ";D;" FEET"
520   PRINT "                   FREQUENCY= ";F;" MHz"
530   PRINT LIN(2)
540   PRINT "OUTPUT DATA"
```

```
550   PRINT
551 Imag1:IMAGE 5X,"PATH LOSS= ",DDD," DB"
560   PRINT USING Imag1;A
570   PRINT
571 Imag2:IMAGE 5X,"EQUIVALENT NOISE OF RECEIVER= ",MDDD," DBM"
580   PRINT USING Imag2;R
590   PRINT
591 Imag3:  IMAGE 5X,"OVERALL SAFETY FACTOR= ",DDD," DB"
600   PRINT USING Imag3;S1
610   PRINT LIN(2)
620   PRINTER IS 16
630   STOP
640   END
```

LIST OF SYMBOLS

B_{if} Receiver intermediate frequency equivalent noise* bandwidth (Hz)

B_{sc} Sub-carrier filter equivalent noise* bandwidth (Hz)

DR Deviation ratio = $\Delta F_{sc}/F_d$

ΔF_c Carrier peak deviation produced by the sub-carrier output voltage (Hz)

ΔF_{sc} Sub-carrier peak deviation produced by the input data voltage (Hz)

F_c Carrier radio frequency (Hz)

F_d Discriminator output low pass filter frequency or maximum data frequency (Hz)

F_ℓ Output filter-lower band edge (Hz)

F_m Modulating frequency (Hz) - in most cases $F_m = F_d$

F_{sc} Sub-carrier center frequency (Hz)

F_u Output filter-upper band edge (Hz)

M Modulation index - $\Delta F_c/F_{sc}$

SNR_c Carrier pre-detection RMS signal-to-noise ratio (db)

SNR_d Data or discriminator output RMS signal-to-noise ratio (db)

SNR_{sc} Sub-carrier pre-detection RMS signal-to-noise ratio (db)

* The noise bandwidth is assumed equal to $\sqrt{1.05}$ x (-3 db bandwidth)

NOTE: All signal-to-noise ratios used in the formulas of Section II are RMS voltage ratios. Power ratios can be found by squaring all terms within the brackets.

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